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SEARCH FOR SHORT-LIVED AXIONS IN A NUCLEAR ISOSCALAR TRANSITION

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Axions, if existing, can cause a strong signal of positron–electron pairs in isoscalar M1 transitions in competition with gamma-ray emission. We searched for such a signal in the 3.59 MeV transition in ¹⁰B with a fourfold Mini-Orange spectrometer. No axion events were found within two percent of the prediction for the standard axion- to γ -ray branching ratio.

A light pseudoscalar Goldstone boson, the axion, has been introduced by Weinberg [1] and Wilczek [2], as a consequence of the global U(1) symmetry proposed by Peccei and Quinn [3] to explain the absence of large P and CP violations in strong interactions. In a treatise of possible axion search experiments, Donnelly et al. [4] discussed the probability for nuclear de-excitation by axion emission in competition with magnetic γ radiation. Subsequent axion searches provided such stringent upper bounds on mass and lifetime that the nonexistence of axions was anticipated [5]. However, the interest in an observable axion was revived recently [6] after the puzzling observation in superheavy collisional systems at GSI of a sharp positron peak at approximately 330 keV, which was later [7] found to be in coincidence with a similar electron peak. Could the observed (e^+e^-) pairs

arise from a “visible” axion with a mass of about 1.68 MeV and a lifetime of $\leq 10^{-11}$ s?

The axion mass and lifetime can be related to one free parameter X , the ratio of vacuum expectation values for two Higgs field components $f \sin \lambda$ and $f \cos \lambda$ with $f = (G_F \sqrt{2})^{-1/2} = 250$ GeV (G_F being the Fermi coupling constant):

$$m_a = 25N(X + 1/X) \text{ (keV)}, \quad (1)$$

where N is the number of active quark pairs ($N = 3$ in ref. [4]). For $m_a > 2m_e$ the axion will predominantly decay in a positron–electron pair with lifetime

$$\tau(a \rightarrow e^+e^-) = 8\pi f^2 X^2 m_e^{-2} (m_a^2 - 4m_e^2)^{-1/2} \text{ (s)}. \quad (2)$$

Searches for axions decaying into two photons with radioactive sources, reactors and beam dumps constrain [5] the mass to < 1 MeV and the lifetime to $< 10^{-6}$ s, whereas a search [8] for decay into positron–electron pairs limits the lifetime to $< 2 \times 10^{-10}$ s. Searches with pseudoscalar- and vector mesons (K^+ , J/ψ and Y) were sensitive to lifetimes of 10^{-11} s due to time dilation of the order of 10^4 . The anomalous magnetic moment of the electron constrains the lifetime to $> 5 \times 10^{-13}$ s [9–12]. In summary, a rather narrow window of lifetimes between 10^{-13} and 10^{-10} s cannot be excluded on the basis of existing experimental evidence. If the observed positron peak is due to an axion with mass 1.68 MeV, its X

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value according to eq. (1) is either $X = 0.045$ or $X = 22$ leading to a lifetime of about 5×10^{-12} s (allowed) or 2×10^{-6} s (excluded). Either of these two X values would lead to contradictions for branching ratios of meson decays in the standard axion model. Quite recently, however, Peccei et al. [13] have succeeded in reconciling the previous unsuccessful searches with an axion of 1.68 MeV in a "viable axion model" which suppresses the coupling to the heavier quarks. Almost simultaneously, Krauss and Wilczek [14] presented a "short-lived axion variant" coupled preferentially to light fermions and stressed with Brodsky et al. [15] the need of new experiments.

In this letter we report on a search for axions in the unexplored region with lifetimes $\tau < 10^{-9}$ s. We looked for the e^+e^- decay of such axions in competition with internal pair creation (IPC) of a magnetic γ -ray transition. Specifically for isoscalar transitions, the branching ratio for (e^+e^-) pair creation from a pseudoscalar decay particle and M1 gamma-decay can be as large [4,16] as 50%. This is three orders of magnitude larger than IPC. As isoscalar transition the 3.59 MeV M1 + E2 transition in ^{10}B was chosen.

The 2^+ , 0 state at 3.59 MeV in ^{10}B decays to the

3^+ , 0 groundstate with a 19% branching ratio. The transition has a mixing ratio [17] $\delta(E2/M1)$ of 1.5 ± 0.6 while the parallel 2^+ , 0 \rightarrow 1^+ , 0 transition of 2.87 MeV is [17] predominantly E2 with $\delta^{-1} < 0.2$. Neglecting internal conversion by atomic electrons, two-photon emission and other higher-order processes, the IPC contributes at the level of 10^{-3} compared with gamma rays in the de-excitation of the 3.59 MeV state. Axion emission would imply a source of (e^+e^-) pairs in addition to the expected (e^+e^-) pairs from IPC. The energy and angular correlations of (e^+e^-) pairs from the 3.59 MeV transition are fixed kinematically. In our experimental arrangement the M1 and E2 IPC is detected with total efficiency ϵ of typically 10^{-4} (see below). The IPC angular correlation between the e^+ and e^- is maximum at relative angle $\theta = 0^\circ$, while in case of the axions the maximum will occur around $\theta = 45^\circ$. The angle between the axes of neighbouring Mini-Oranges is 60° (fig. 1), which causes an axion decay to be seen with somewhat higher efficiency than IPC; a numerical estimate gave $\epsilon_A \approx 1.5\epsilon$, assuming that the axions are emitted isotropically. The nuclear axion-decay rate (in the case of existing axions) is predicted in ref. [4] to be as large

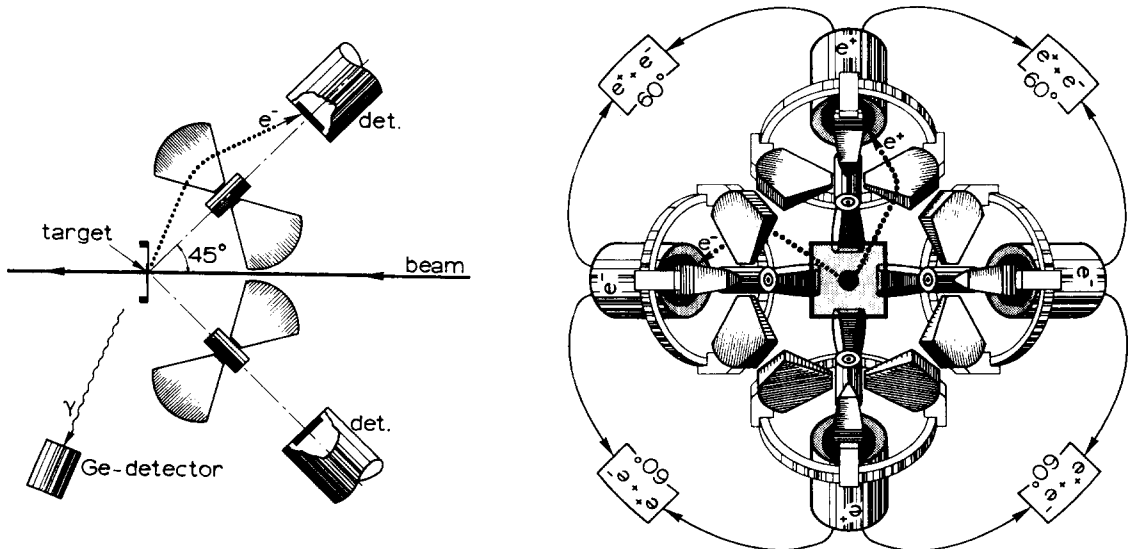


Fig. 1. Fourfold Mini-Orange arrangement for the axion search. To the left a view of the horizontal plane and to the right a view upstream along the beam axis. The hypothetical axion $\rightarrow e^+ + e^-$ decay is supposed to occur inside or closely (at μm distance) behind the target layer. In the left part of the figure an e^- particle is indicated, while the corresponding e^+ particle will be detected by a neighbouring e^+ detector (out of plane).

as $I_a = 0.39 I_\gamma(M1)$. The number of observed pairs can now be written as:

$$N(e^+e^-)/\epsilon = \{0.39 \times 1.5 + \alpha_\pi(M1)\} I_\gamma(M1) + \alpha_\pi(E2)I_\gamma(E2), \quad (3)$$

where ϵ is the efficiency. Theoretical IPC coefficients α_π can be obtained from ref. [18]. If axions indeed exist then the first term ($= 0.585$) will dominate since the others are of order 10^{-3} .

In the experiment the 3.59 MeV state in ^{10}B was excited in inelastic scattering of 7 MeV protons by a

^{10}B target of 1 mg/cm^2 . Using a fourfold Mini-Orange system [19] with two detector systems for e^+ and two for e^- detection, we registered prompt (e^+e^-) signals and their energy sums. The four spectrometers were set at a backward angle of 45° with respect to the incident proton beam. This is shown by a view in the horizontal plane in fig. 1 (left). The axes of opposite Mini-Oranges (with the same polarity) made an angle of 90° with each other, those of neighbouring ones (with alternating polarity) one of 60° . For clarity fig. 1 (right) shows four equal Mini-Orange systems, each composed of four magnets and the e^+ and e^- sys-

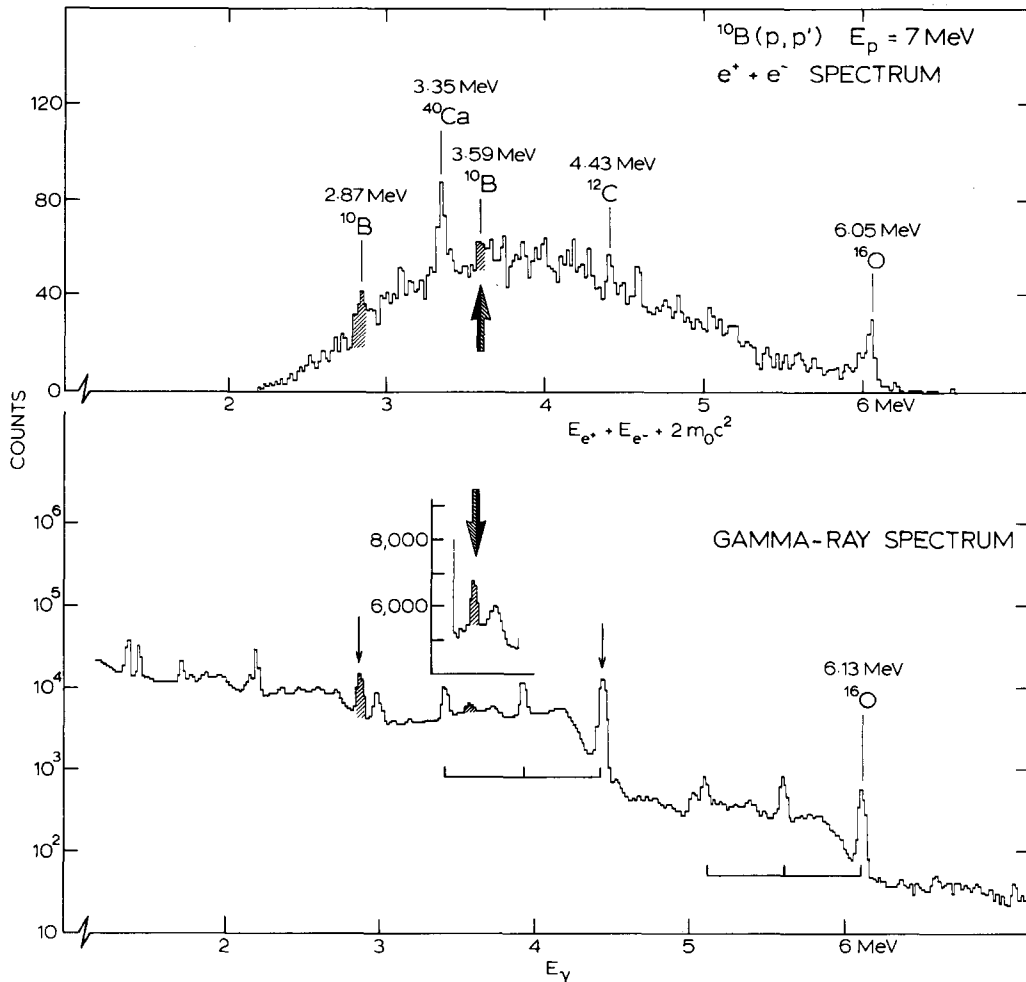


Fig. 2. Sum of four $e^+ + e^-$ pair spectra (top) compared with a simultaneously recorded γ -ray spectrum (bottom) using a Ge detector, following the $^{10}\text{B}(p, p')$ reaction at 7 MeV. In case of an existing axion with mass of 1.68 MeV and lifetime $5 \times 10^{-12} \text{ s}$, the prediction by Donnelly et al. [4] corresponds to a peak at 3.59 MeV with height of over 1000 counts.

tems being only different by inversion of their magnetic fields. In reality the present experiment was limited by the available magnets so that two four-gap and two five-gap systems had to be used. Since the latter magnets were relatively weaker, the overall features of the four magnet systems were similar, with maximum transmissions around 1.3 MeV.

The Mini-Orange spectrometers were equipped with 300 mm² Si(Li) detectors: two with a thickness of 3 mm and two with a thickness of 5 mm. With the KVI data acquisition system (VAX 750) the twofold coincidences were registered on magnetic tape for off-line analysis.

Fig. 2 (top) displays the essential result: the sum of the (e^+e^-) pair spectra from the four neighbouring detector combinations in which we can look for a possible axion signal in competition with expected IPC peaks. The (e^+e^-) spectrum is compared with a simultaneously recorded spectrum of gamma rays (bottom) using a Ge detector. It is apparent that the internal pair peaks of the two isoscalar transitions at 2.87 MeV and 3.59 MeV in ¹⁰B are only weakly visible in the (e^+e^-) spectrum.

Interestingly, two rather prominent peaks at 3.35 and 6.05 MeV show up in the sum spectrum. They have no counterpart in the γ -ray spectrum and belong to totally converted E0 transitions in ⁴⁰Ca and ¹⁶O respectively, which are to our knowledge the only two existing E0 transitions in nature depopulating first excited states between 3 and 7 MeV. The spectra of scattered protons, recorded separately, indeed showed a significant content of ¹⁶O (and ¹²C) impurity in the target. A tracer impurity causes in the pair spectra the appearance of the E0 transition in ⁴⁰Ca. The 6.05 MeV transition in ¹⁶O occurs just above energy threshold and also in the extreme upper transmission range of the Mini-Oranges. Furthermore, it is observed despite the fact that the two 3 mm Si(Li) detectors had insufficient stopping power for most of the e^+ and e^- pulses. Evidently, the arrangement is hypersensitive for detection of totally converted E0 transitions.

The background of the pair spectrum is complex, containing a continuum distribution following ¹⁰B(p, α) distributions from pairs created inside the vacuum walls, e^+ and e^- particles from e.g. the E0(¹⁶O) transitions which pass through the detectors. Yet, the main part of the spectrum belongs to IPC coincidences and not to e.g. Compton scattered γ rays since the yield of

$e^+ + e^+$ and $e^- + e^-$ type combinations is less by an order of magnitude than the $e^+ + e^-$ pairs. In the γ -ray spectrum all transitions of sufficiently short half-life are Doppler broadened and/or shifted. The ¹⁰B 2.87 and 3.59 MeV γ rays show up strongly. The spectrum also shows a number of ²⁷Al γ rays produced in the walls of the Mini-Orange vacuum chamber, together with the 4.43 MeV E2 transition in ¹²C and the 6.13 MeV E3 transition in ¹⁶O (target impurities), visible by photo peaks, single- and double-escape peaks.

Efficiency calibration for IPC detection was obtained as follows: at the low energy side the system was calibrated (i) internally at 1.85 MeV with the 2.87 MeV transition in ¹⁰B (> 98% E2) and (ii) externally at 1.733 MeV using the 2.755 MeV E2 transition in ²⁴Na with theoretical [18] IPC's of 7.4×10^{-4} respectively 7.0×10^{-4} . (iii) A comparison of the intensity of inelastically scattered protons from the 4.43 MeV level in ¹²C with that from the 3.59 MeV level in ¹⁰B, the ratio being 0.6, showed us that only a fraction of the corresponding γ -ray intensity in ¹²C is produced in the target and apparently most of it originates in the walls of the chamber. The ratio of γ -ray intensities was determined to be 0.5 using experimental data for differential and total cross sections for ¹⁰B(p, p') [20] and ¹²C(p, p') [21,22] inelastic scattering at 7 MeV under 135°. The obtained gamma-ray intensity was then used together with the internal pair intensity and the theoretical [18] IPC of 1.3×10^{-3} for an E2 transition of 4.43 MeV to internally determine the efficiency of the Mini-Orange system at 3.41 MeV. All three efficiency calibrations are equal to a value of $\epsilon = 2.3 \times 10^{-4}$ within 35%.

The isoscalar 3.59 MeV transition has in the (e^+e^-) pair spectrum roughly the same intensity as the parallel 2.87 MeV transition used for internal calibration. The branching ratio of the 3.59 MeV pair peak was determined to be $(2.1 \pm 1.1) \times 10^{-3}$ which is consistent with internal pair creation, α_π being 1.0×10^{-3} for a 28% M1 and 72% E2 transition. The full strength of axion decay with the Donnelly value of $I_a = 0.39 I_\gamma$ (M1) for an axion of 1.68 MeV would have caused a peak height of over 1000 counts or two orders of magnitude larger than as observed. With 90% confidence our result corresponds with a boundary being 54 times smaller than the value predicted by the standard model [4]. In recent more sophisticated axion models [13,14] the conjectured axion couples to one or two

quark pairs [$N = 1$ or 2 in eq. (1)]. In the case of only two light quarks, no coupling is expected to a magnetic isoscalar transition. In the case of coupling to two quark pairs our experiment leads with 90% confidence to a boundary factor of 31 with respect to the theoretical prediction in the case of existing axions. Consequently our search yields no evidence for the existence of a standard ($N = 3$) or a viable ($N = 2$) axion.

After evaluation of our experimental data, we became aware of IPC measurements in the early decades of nuclear physics, when axions were not yet advocated, but when (e^+e^-) angular correlations were used as a probe for distinguishing multipolarities of high-energy γ -rays. We were both surprised and impressed by the angular correlations reported for the 3.59 MeV transition in the clean reaction ${}^9\text{Be}(d, n){}^{10}\text{B}$ by Gorodetsky et al. [23]. They used scintillation counters with inherently two orders of magnitude less energy resolution than our Si(Li) detectors (though this resolution is partly spoiled by Doppler broadening), and could hardly separate a strong 3.37 MeV transition in ${}^{10}\text{B}$ from the 3.59 MeV isoscalar transition in ${}^{10}\text{B}$. Yet, their angular distribution shows no enhancement near 45° where the standard axion would have given at least one order of magnitude larger signal than measured. Also, a recent reanalysis by Calaprice et al. [24] of IPC data from Warburton et al. [25] shows no evidence for axion competition in either isoscalar or isovector M1 transitions.

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